MATLAB/SIMULINK Based Simulations on State of Charge on Battery for Electrical Vehicles

1 S. VimalRaj, 2 G. Suresh Kumar, 3 Sunil Thomas, 4 Nithiyananthan Kannan

1 Department of Electrical and Electronics Engineering, Sri Krishna College of Technology, Coimbatore, Tamilnadu, India. E-mail: vimalraj@skct.edu.in
2 Department of Electrical and Electronics Engineering, Karpagam College of Engineering, Coimbatore, Tamilnadu, India. E-mail: sureshkumar.g@kce.ac.in
3 Department of Electrical and Electronics Engineering, Birla Institute of Technology and Science, Pilani, Dubai, U.A.E. E-mail: sunil.thomaspr@gmail.com
4 Department of Electrical Engineering, Faculty of Engineering, King Abdulaziz University, Rabigh, Saudi Arabia. E-mail: nmajaknap@kau.edu.sa

Abstract

Electric Vehicles represent one of the key technologies to reduce CO2 emissions; their effective potential in real world driving conditions strongly depends on the performance of their Energy Management System. Range anxiety is an obstacle to the acceptance of electric vehicles caused by driver’s uncertainty regarding their vehicle’s state of charge and the energy required to reach their destination. Another one of the shortcomings of Electric Vehicle technologies is the high cost of batteries. Any enhancement in such points will make Electric Vehicles a well-built competitor for IC engines. The material cost for the Zebra battery is much lower compared with lithium batteries. In addition the cycle life better than 1000 cycles in zebra battery. Supercapacitors are one of the major components which play vital role in energy storage area. It also reduces the stress to batteries. The Multiple sources are modeled and analyzed by connecting the supercapacitor in parallel with ZEBRA battery. The combination shown was much cost effectives and range reassurance with addition battery maximum power demand will be reduced and also the internal power losses get minimized. The model is done by MATLAB®/Simulink® environment and the output results had been analyzed for the different vehicles input parameters. The results are consolidated based on the range of vehicle and State of charge of the battery. The main objective of this paper is to develop standard operating procedure for the design, simulation and consolidated analysis of the Hybrid Electric Vehicles.

Keywords: ZEBRA, SOC, Hybrid, MATLAB/SIMULINK, Super-capacitor, Electrical Vehicle.


1 Introduction

The attraction towards electric cars in the developing nations of Asia and Pacific had increased over past few decades. Figure 1 indicates the growth trend of electric vehicle as the year progress.

With the increasing interest in electrically powered vehicles, there has been a great deal of attention paid to improving batteries and producing new types of batteries with higher energy density than lead acid. Additionally, there has been great interest in using peak power buffers to mitigate against the high battery current transients encountered during urban driving. Overall, the electric vehicle is more energy efficient, environmentally friendly, and cleaner than the vehicle that relies on fossil fuels, especially when smart grids have become omnipresent. By popularizing the electric vehicle, the environmental and economic costs of vehicles can be significantly reduced. Hence, the electric vehicle has attracted the attention of academia as well as industry in the recent decades. Huge lot of research work has been reported on computer applications on Electrical Engineering which helps and applied on Electrical vehicles.

With the development of the electric vehicle, the techniques of charging piles- which are an essential component in the electric transportation system- have rapidly progressed as well. Most of the automobile manufacturers around the world have paid a large amount of financial resource to the research of charging piles, since the charging technique is, to some extent, key to the success of the electric vehicle. The rest of this paper is organized as follows. In Section II, the technical fundamentals, including the technical background, theoretical principles, and mathematical models of zebra battery are given. It then reviews about the super capacitors and their pros and cons in Section III. Most importantly, the potential research directions for electric vehicle technology, especially analyzing and modeling of the hybrid Energy Management System (EMS), are pointed out in Section IV. Finally, this paper is concluded in Section V.
1.1 Modeling of Electrical Vehicles (EV)

With the help of technical assistance the battery based electric vehicle has been mathematical model had been developed and results were calculated. Electrical Vehicle analytical calculations had reported in lot of research papers. The mathematical model has been converted into simulation model and performance of the EV has been carried out and tested in MATLAB/SIMULINK environment. [43-46]

![Schematic view of a simple EV](image)

A. Resistive Forces Calculations

**Drag resistance (F\textsubscript{L})**

The drives forward resistance is based on wind force.

\[ F\textsubscript{L} = \frac{1}{2} \rho A v^2 c\textsubscript{w} \]  

Here, 
\( \rho \) – Air Density, \( A \) – Frontal area of vehicle, \( c\textsubscript{w} \) – Drag coefficient and \( v \) – Driving velocity of vehicle.

**Rolling resistance (F\textsubscript{R})**

This resistance is mainly due to the friction between wheels and road. It is calculated as

\[ F\textsubscript{R} = m \cdot g \cdot f\textsubscript{r} \]  

Here, 
\( m \) – Mass of the vehicle, \( g \) – Acceleration due to gravity and \( f\textsubscript{r} \) – Coefficient of rolling friction.

**Bearing and Mechanical Friction (F\textsubscript{B})**

The rotating mechanical parts such as bearing, shaft and others offer some resistance. This resistance not only depends on their installation with proper alignment during manufacturing but also on lubrication.

\[ F\textsubscript{B} = m \cdot g \cdot k\textsubscript{B} \]
Here, $k_B$ – Constant for a vehicle which accounts for bearing and mechanical friction. Value of $k_B$ is assumed to be 0.005 for the vehicle.

### B. Calculation of Vehicle Shaft and Motor Parameters

**Shaft Force ($F_S$)**

$$F_S = F_L + F_R + F_B$$  \hspace{1cm} (4)

**Shaft Power ($P_S$)**

$$P_S = F_S \cdot v$$  \hspace{1cm} (5)

**Shaft Speed ($n_S$)**

$$n_S = \frac{60 \cdot v}{\pi \cdot D_{wheel}}$$  \hspace{1cm} (6)

**Shaft torque ($M_S$)**

$$M_S = F_S \cdot R_{wheel}$$  \hspace{1cm} (7)

**Motor torque ($M_m$)**

$$M_m = \frac{M_s}{\eta_m \cdot i}$$  \hspace{1cm} (8)

**Motor Speed ($n_m$)**

$$n_m = n_s \cdot i$$  \hspace{1cm} (9)

**Motor Power ($P_m$)**

$$P_m = \pi \cdot n_m \cdot M_m$$  \hspace{1cm} (10)

The efficiency curves for considered Asynchronous machine (ASM) is available from which motor efficiency is calculated.

![Efficiency-Torque-Speed Curve of ASM – Inverter System](image)

**Figure 3** Efficiency-Torque-Speed Curve of ASM – Inverter System

### C. Calculation of Vehicle Acceleration

The motor rated torque. Gearbox in between motor and vehicle shaft is responsible for speed transition from shaft to wheel. From motor parameters, acceleration can be calculated as follows.

$$M_{wheel} = i \cdot M_m \cdot \eta_g$$  \hspace{1cm} (11)
Force on wheel \( F_{\text{wheel}} \) \( \text{wheel} = \frac{M_{\text{wheel}}}{r_{\text{wheel}}} \) \hspace{1cm} (12)

Acceleration \( (\alpha) \)

\[ \alpha = \frac{F_{\text{wheel}}}{m \cdot \lambda} \] \hspace{1cm} (13)

2. Hybridization of Battery Based Super Capacitor

Two or more technical concepts integration derive innovate concept of the Hybrid Energy Storage (HES) To increase the overall performance the combining two different type of storage systems is implemented. The single store system has many disadvantages such as low power rating, less life span, less reliability etc. Hence the hybridization gives high energy rating, high speed response and shorter charging duration. Apart from these advantages the super capacitor able to reduce the burden on batteries and also it enables the battery life. Many literatures support the use of batteries and super capacitors as a combined unit. This integration is able to achieve high storage in capacity and very fast charging time. In few real time applications such as wind energy power plants, electric vehicle and micro grid etc. are used this integration of super capacitor and battery unit. The excess Photo voltaic energy is stored in the battery and power management is done by supercapacitors. Hence it is mandatory to find out the best possible combination of energy storage systems based on the applications and its requirements.

2.1 Zebra Battery Model

Coetzer, in 1978 at CSIR devise the ZEBRA battery. MED-DEA, Stabio, Switzerland was the first industrialized production stated of the ZEBRA cell. In the ZEBRA technology, the electrode material is a nickel powder and plain salt, the electrolyte and separator is \( \beta \)-Al2O3 -ceramic that conductive for Na+ ions but insulator for electrons. The ZEBRA battery operates at temperature range of +270ºC to 350ºC.

In electric vehicles, the battery model is the strong candidate which plays a vital role as an energy source. Many researchers and published were done in the field models. An ultimate battery model is the key point for the successes of total system. The battery model must be robust and the chemical phenomena such as the diffusion effects, ohmic resistance, self-discharging and mass transport limitations are to be predict accurate battery voltage, current, and state-of-charge (SOC). There are several battery models, reported in the literature, aimed to reflect the battery characteristics. The simplest battery model is shown in Fig. 4 consisting of an ideal voltage source (EO) and a constant equivalent internal series resistance (ESR).

![Figure 4 Simple equivalent circuit of the battery](image-url)
Calculation of Battery Parameters

By considering the constant auxiliary consumption $P_{aux}$, battery power is calculated as

$$P_B = P_{aux} + \frac{P_m}{\eta_m} \tag{17}$$

From the discharge curves provided by the battery manufacturer, battery no-load voltage $U_{BO}$ and internal Resistance $R_{BI}$ can be calculated. The battery current $I_B$ can be calculated,

$$I_B = \frac{U_{BO}}{2R_{BI}} - \sqrt{\left(\frac{U_{BO}}{2R_{BI}}\right)^2 - \frac{P_B}{R_{BI}}} \tag{18}$$

SOC of the battery

$$SOC = \frac{(Q_N - Q)}{Q_N} \tag{19}$$

3. SUPERCAPACITOR

A supercapacitor is an electrochemical double layer capacitor (EDLC) which is widely used in electric vehicle and Energy storage systems. Energy storage capability of the supercapacitor has unique feature, by which the component has been made choice by some application where the high power density is required.

This unique property will made the component to ensure it is ability to handle a fast fluctuation in energy level. Theory about the supercapacitor was first released by Hermann Von Helmholtz. In supercapacitor there is no chemical reaction involved in it, only having interaction between the conductor and the electrolyte inside the capacitor. The electrodes of a supercapacitor are porous in structure made of carbon material. Electrolyte is deposited around the electrode of the supercapacitor. As shown in Figure 5 arranged structure which gives the larger conduction area to the supercapacitor. The electrolyte present inside the supercapacitor will have free charge carrier which termed as ions and the behavior of ions is determined by the diffusion and electrostatic relative

![Figure 5 Schematic of an electrochemical double-layer capacitor](image)

With the supercapacitor due to the diffusion reaction the ions which present in the electrolyte are evenly distributed the time of completely discharge state. While supercapacitor gets charged, Electric field is created in between the electrodes of the
supercapacitor. The evenly distributed ions are get attracted toward that field as result of the field the ions started to separate. Thus the supercapacitor has high power density and lower energy density compared to any other energy storage device. Supercapacitor have a distinctive character such as faster charge and discharge rate and high recyclability which take over the battery performance.

By alleviate the battery it will gives space for the longer life of battery, narrow charging and discharging and also improve the system efficiency by boosting the peak power of the system. Supercapacitor can act as greater substitute for battery by connecting parallel with battery for charging and discharging high power in short time. This leads the battery for longer life. The state of charge variation in case of battery will affect the life of the battery. But in supercapacitor whatever the SOC the charging cycle will not affect that much greater.

**3.1 Supercapacitor Modelling**

The modelling of super capacitors is a latest technology which has great attraction towards researchers. These super capacitors are called as ultra-capacitors or double layer capacitors. The energy is stored between the positive and negative electrode and it don’t affected by chemical reaction. During the process of charging, charged ions move through the electrolyte between the attractive polarities. Super capacitors are having lot of advantages compare to other storage devices. The advantages are having high efficiency around 80% to 95%, more than 100000 cycles which enhances the life span, more power density ranges from 500 to 5000 W/kg and response time is less than 5 ms. High resistance from deep discharges. Super capacitors are implemented such as developed as modules with serial, parallel connections or combine both. Figure 6 indicates the supercapacitor cell circuit which normally of 3V density. The two branches models are slow branch and main branch.

![Figure6 Super capacitor cell equivalent circuit diagram](image)

The main cell communicates to the response during the charging process of the super capacitor in the range of charging time. The resistance $r_1$ represents the series resistance and it indicates the waste power dissipated as heat. As per the capacitor $C_1$ highly depends on the voltage $V_1$ as per equation (20). The $C_0$ is the constant capacitance in Farads (F) and $C_v$ is constant.

$$C_1 = C_0 + C_v V_1$$  \(20\)

The slow branch indicates the internal energy distribution the end of charging cycle. The leakage resistance $R_f$ indicates the leakage current in mode. This self –
discharge property in the equivalent is neglected and equation (21) indicates the voltage of the super capacitor module \( V_{sc} \)

\[
V_{sc} = N_p U_{sc} = N_s (V_1 + R_1 \frac{I_{sc}}{N_p})
\]

(21)

Where \( N_p \) and \( N_s \) are the number of parallel connection and number of supercapacitor cells in series and, respectively. Also, \( I_{sc} \) is the cell current and \( U_{sc} \) is the voltage of the supercapacitor module.

The slow cell, the voltage \( V_2 \) can be derived by:

\[
V_2 = \frac{1}{C_2} \int i_2 \, dt = \frac{1}{C_2} \int \frac{1}{R_2} (V_1 - V_2) \, dt
\]

Across the capacitor \( C_1 \) the voltage \( V_1 \) on the cell is given by:

\[
V_1 = -C_0 + \sqrt{C_0^2 + 2C_0 Q_1}
\]

(23)

The instantaneous charge of \( C_1 \) is considered as \( Q_1 \) and it derived at.

\[
Q_1 = C_0 V_1 + \frac{1}{2} C_1 V_1^2
\]

(24)

4 Simulations Using MATLAB/SIMULINK for Hybrid Energy Sources Based State of Charge

Simulations results of terminal voltages of both energy sources are shown in Figure 7, while Figure 8 shows the demand current, ZEBRA battery and super capacitor currents. The terminal voltage variation is very important on the battery life as well as inverter design. The variation of the voltage defined as the dip voltage that occurs regarding to discharging current.
The different inputs of EV can be consolidated and tabulated as shown in Table 1.

**Table 1** Simulated range versus the velocity of vehicle

<table>
<thead>
<tr>
<th>Velocity of Vehicle (m/s)</th>
<th>Li ion Battery</th>
<th>Pure Zebra Battery</th>
<th>Zebra Battery + Supercapacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_1 (A)$</td>
<td>$SOC%$ Range (Km)</td>
<td>$I_1 (A)$ $SOC%$ Range (Km)</td>
</tr>
<tr>
<td>22.5</td>
<td>150</td>
<td>25 81</td>
<td>180 25 67</td>
</tr>
<tr>
<td>13.0</td>
<td>78</td>
<td>61 50</td>
<td>93 53 50</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>75 32</td>
<td>60 60 32</td>
</tr>
</tbody>
</table>
The result shown in Figure 10 and Table 1 indicate that the combination of the zebra battery and supercapacitor will improve the state of charge of the battery. With the improvement on the SOC of battery we can overcome the range anxiety problem. The cost wise the zebra cells are cheaper compare to the lithium batteries. The model developed is much more cost effective. While using the zebra battery the failure of cell in multiple packages will not affect the system performance. By improving the SOC of battery the distance cover by the vehicle is improved. Thereby the overall performance and efficiency of the electric vehicle system is improved.

5 Conclusion

The research work carried out to check the performance of the combination of zebra battery and super capacitor support system for Electrical Vehicle. Each power supporting system has been analyzed thoroughly with suitable mathematical equations and impact has been discussed elaborately. The MATLAB/SIMULINK based simulation model has been developed and analysis has been carried out to find the performance of the overall support system. The proposed model able to increase the life of the battery by 15% which in turn makes high impact on EV maintenance cost. The proposed zebra battery model can be analyzed in future into the thermal mode to reduce the temperature which improves the performance further.

References


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Biographies

**Dr. S. Vimalraj** is currently working as Associate Professor in the Department of Electrical and Electronics Engineering, Sri Krishna College of Technology, Coimbatore, Tamil Nadu India. He had completed his Ph.D in the area of Very-large-scale integration (VLSI). He is an active member of International Society of Technical Education, India His area of interest includes VLSI, Renewable energy sources.

**Mr. G. Sureshkumaar** is currently working as an Assistant Professor in the Department of Electronics and Instrumentation Engineering, Karpagam College of Engineering Coimbatore. He had completed his Bachelor of Engineering in Electrical and Electronics Engineering, 2012 and Master of Engineering in Power Systems Engineering in 2015. He is currently pursuing his Ph.D in the area of Power Electronics Engineering, Anna University, Chennai, India. He is an active member of International Society of Technical Education, India His area of interest includes Power Electronics, Renewable Energy and LABIVEW.

**Dr. Sunil Thomas** is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering, BITS Pilani, Dubai Campus, U.A.E. He completed his Ph.D in Electrical Engineering from BITS Pilani in the year 2015. His areas of interests are Electrical machines, Power Electronics, Electric Drives and Power system engineering and have 10 years of teaching/research experience.
Prof. Dr. Nithiyananthan Kannan is currently working as a Professor in the Department of Electrical Engineering, King Abdulaziz University, Rabigh, Saudi Arabia. He has 19 years of teaching/research experience. He completed his PhD in Power System Engineering from the College of Engineering, Guindy Campus, Anna University, India in 2004. He is an active member of IET (UK) and he received Charted Engineer title in 2016 from Engineering Council, UK. His areas of interest are computer applications to power system engineering, modeling of modern power systems, renewable energy, smart grid and micro grid.